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Biorefinery Feedstock Production on Conservation Reserve Program Land

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Technology that would enable use of lignocellulosic biomass for biorefinery feedstock is under development. The 2002 Farm Bill permitted managed harvesting of biomass from Conservation Reserve Program (CRP) land. This study was conducted to determine the cost to procure, harvest, store, and transport to a biorefinery a flow of lignocellulosic biomass feedstock produced on CRP grasslands in the southern Great Plains and to determine how policies that restrict harvest frequency and days influence cost. Policies that restrict harvest days per year and the frequency of harvest would increase the cost to deliver biomass feedstock.

A biorefinery is a factory that will convert biomass (in the case of grasses, any part of the plant or the entire plant) into a variety of intermediate and final products (Kamm and Kamm; Ohara; McKendry). Several competing conversion technologies that would enable use of lignocellulosic biomass for biorefinery feedstock are under development (McKendry). Examples include gasification, pyrolysis, liquefaction, fermentation, and anaerobic digestion (McKendry). A potential advantage of biorefineries relative to conventional crude oil refineries is that feedstocks composed of atmospheric carbon would be used to produce products from which the carbon would eventually be recycled to the atmosphere. The carbon-chain components of plant material could be refined to chemicals that in recent decades have been derived from petroleum.

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Feedstock cost will be an important factor in determining the economic viability of a biorefinery. Large acreages of grasslands have been re-established on Conservation Reserve Program (CRP) land. Some have suggested the use of CRP-enrolled acres for production of biorefinery feedstock (Downing, Walsh, and McLaughlin; Goodman, Coady, and English; Martin et al.; Walsh, Becker, and Graham; Walsh et al.).

The CRP was established by enabling legislation in the 1985 Farm Bill (Martin et al.; Swanson, Scott, and Risley; Sullivan et al.). It set aside highly erodible and environmentally sensitive acres of cropland under 10–15 year contracts. Land under CRP is planted to conservation crops such as perennial grasses and trees. Landowners receive an annual rental payment from the federal government. The purpose of the CRP is to cost-effectively assist producers in conserving and improving soil, water, and wildlife resources (Sullivan et al.; U.S. Department of Agriculture, 2003). Martin et al. reported that the CRP could also be used to mitigate some of the problems associated with excess crop production, as well as protect erodible cropland.

The 1985 Farm Bill generally provided that no commercial use could be made of land enrolled in the CRP, but permitted haying or grazing during droughts or similar weather-related emergencies. Restrictions on the use of CRP acres have been debated since the onset of the program. Hipple and Duffy reported that restrictions imposed upon management of CRP acres would constrain development of bioenergy crops such as switchgrass. Ray, Ugarte, and Tiller have suggested that enabling use of CRP acres for production of bioenergy crops and expansion of CRP acres could result in higher crop prices, decreased soil erosion, reduced government outlays for conventional farm programs, and increased rural income. They also note that land placed in the CRP could be brought back into crop production if the need arose. However, they don't explain how this might influence the functioning of an established biorefinery industry that depended upon feedstocks produced on CRP acres.

In anticipation of a profitable lignocellulosic biorefinery business model, amendments were made to the management of CRP land. The Farm Security and Rural Investment Act of 2002 (FSRIA) permitted managed haying, grazing, and biomass harvesting of CRP grassland in accordance with a conservation plan (U.S. Department of Agriculture, 2003). To ensure the environmental benefits attributable to grassland birds and other species, the Farm Service Agency (FSA) incorporated recommendations from grassland ecologists into the legislation (Cunningham; U.S. Department of Agriculture, 2003). Acres that are used for grazing, haying, or on which biomass has been harvested are assessed a 25-percent reduction in annual rental payment. The legislation also limits managed harvest or grazing to a maximum of once every three years.

State FSA committees, in consultation with state technical committees, are authorized to determine the beginning of the primary nesting and brood-rearing season during which harvest would not be permitted. No special dates were determined for harvesting biomass for biorefinery processing. However, since biomass harvesting involves mowing, similar to mowing necessary for haying, the applicable dates would be expected to be the same as those for the haying period.

Objective

The objective of the research reported in this article is to determine the cost to procure, harvest, store, and transport a flow of lignocellulosic biomass feedstock produced on CRP grasslands to a biorefinery and to determine how policies that restrict harvest days and frequency influence cost. There are several unresolved issues regarding the use of CRP lands. It is anticipated that a cost-efficient lignocellulosic biorefinery would process continuously and require a rather substantial quantity of feedstock, perhaps several thousand tons per day. Given the expected cost to harvest, store, and transport bulky feedstock from fields, a biorefinery that relied exclusively on feedstock from CRP acres would most likely be located in a region with a high concentration of CRP land. In 2004, a total of 34.9 million acres were enrolled in the CRP. However, with a few exceptions, these acres were scattered widely across the country.

Most of the CRP acres have been reseeded to indigenous species that once established are very persistent. However, they are not high yielding and given that by policy, harvest is restricted to once in three years, it is not known if there is a sufficient concentration of material to provide inexpensive biorefinery feedstock. Biorefinery location will be an important issue. Another issue has to do with the length of the harvest season. A wide harvest window would enable the use of harvest machines and harvest crews over many months. The most important feedstock component is carbon. Since, carbon is stored in the lignin and cellulose chains, the timing of harvest is not expected to be critical. Harvesting grass to obtain carbon is more similar to harvesting trees to obtain lumber than it is to harvesting forage for protein and other nutrients for livestock feed.

Sullivan et al. identified three large contiguous regional economies most significantly affected by CRP payments. They are the Northern Plains Crescent that includes counties in Montana, North Dakota, South Dakota, and Minnesota; the Southern Plains Ellipse that includes counties that form a north–south ellipse in Kansas, Colorado, Oklahoma, New Mexico, and Texas; and the Southwestern Corn Belt that includes counties in Iowa and Missouri. Because of differences in expected snowfall and severity of winters, the harvest window is assumed to be greater in the Southern Plains Ellipse than in either the Northern Plains Crescent or the Southwestern Corn Belt.

While use of CRP lands is permitted, it remains to be seen if grasses produced on these acres could provide an economical biorefinery feedstock. A comprehensive modeling approach is developed and implemented by considering CRP acres from counties located in the Southern Plains Ellipse. Since it is assumed that a biorefinery will require a continuous flow of material throughout the year, the model accounts for timing of harvest, storage, and transportation, factors important in determining the cost to deliver feedstock.

Prior Studies

Interest in the cost of delivering potential feedstocks has been the subject of a number of studies. English, Short, and Heady estimated the cost of using crop residues as auxiliary fuel in coal-fired power plants in Iowa. Nienow et al. estimated the cost of woody biomass (Salix trees) co-firing with coal in electricity production in Northern Indiana. Kaylen et al. studied the economic feasibility of producing ethanol from lignocellulosic feedstock including crop residues, woody biomass, and dedicated energy crops in Missouri. However, none of these studies considered the timing issues. Tembo, Epplin, and Huhnke considered part of the timing issues, but ignored a critical factor. They did not place any restrictions on the number of acres that could be harvested during a time period and concluded that it was optimal to harvest more than half of total lignocellulosic biomass tonnage required for an entire year in a single month.

The current model differs from prior models in that harvest is limited to CRP acres and a defined harvest unit is incorporated into the model as an integer activity. The quantity of biomass harvested per month is constrained by the number of harvest days per month and the number of endogenously determined harvest units. Storage is accounted for by month and can be located in the field or at the biorefinery. Shipments of biomass to the biorefinery can also be done in each of the 12 months. This modeling framework more nearly characterizes the problem than prior research and should provide results that could enlighten policy makers relative to the economic tradeoffs associated with policies that restrict harvest season length and frequency of harvests.

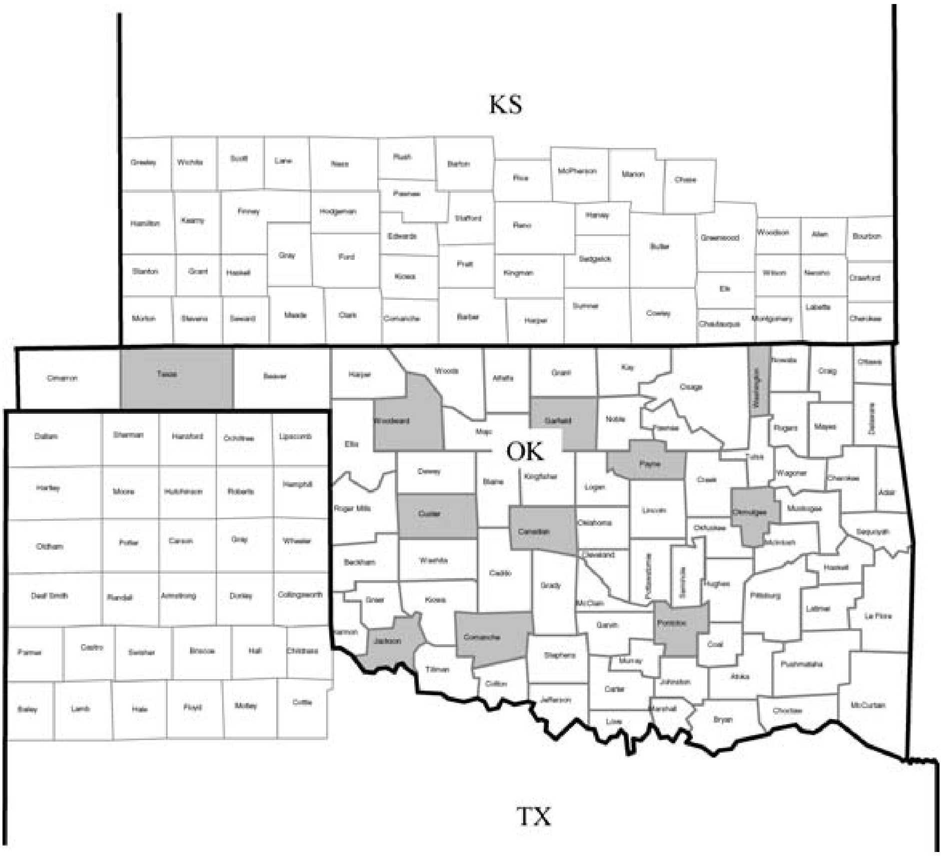
Case Study

The Southern Plains of Kansas, Oklahoma, and Texas include an area of concentrated CRP acres in the Southern Plains Ellipse and a wide harvest window (Sullivan et al.). A region that includes 52 Kansas counties, 77 Oklahoma counties, and 32 Texas counties has a combined CRP enrollment of more than five million acres on which perennial grasses, including native prairie grasses, have been established (figure 1).

A multi-region, multi-period, mixed integer mathematical programming model was constructed. Appendix A provides a description of the model. The model was designed and solved to determine the cost to procure, harvest, store, and transport a flow of biomass to a biorefinery and identify the optimal biorefinery location from among several potential sites. CRP acres were based upon 2004 enrollment (U.S. Department of Agriculture, 2004). Biomass yield estimates for the grasses produced on CRP acres were based upon models described by Sala et al. Expected biomass yields differ across months due to stage of growth and field losses that occur after plant maturation. Yield adjustment factors were used to account for expected differences in harvestable material across months. These were obtained from professional agronomists.

Three different biorefinery sizes were modeled based upon biomass feedstock requirements of either 1,000, 2,000, or 4,000 dry tons per day. For each biorefinery size, storage capacity at the biorefinery was assumed equivalent to the tons of biomass that could be processed in three weeks (i.e., 21,000, 42,000, and 84,000 tons for the 1,000, 2,000, and 4,000 tons-per-day biorefineries, respectively). Minimum inventory at the biorefinery facility was assumed to be equal to zero. Storage losses at the biorefinery were assumed to be equal to 0.1 percent per month. Precise estimates of storage losses are not available. The estimate used was provided by forage storage specialists. The biorefinery was expected to operate 350 days per year.

Figure 1. Map of study region in Kansas, Oklahoma, and Texas, including the eleven counties (shaded) modeled as potential biorefinery locations



Eleven counties in the region were selected as possible biorefinery locations (figure 1). The plant locations were selected on the basis of biomass relative density, proximity to the biomass-producing counties, and availability of road infrastructure. A city approximately at the center of the county was used to represent the county as a whole. The distance between any biomass-supplying county and any plant location was estimated by the distance between the two county's representative point (i.e., the centrally located city).

Assumptions regarding the type of harvest system were based upon results of Thorsell et al.'s cost study of lignocellulosic biomass harvest. Based upon their findings, it was assumed that the biomass would be harvested in large rectangular solid bales, stored in or near the production fields, and transported by truck to the biorefinery when needed. It was assumed that harvest would be conducted by harvest crews, either independent operators, or crews coordinated by central management of the biorefinery. The model endogenously determines the number of harvest units. Thorsell et al. designed a harvest unit as a coordinated set of harvest machinery that includes ten laborers, nine tractors, three mowers, three rakes, three balers, and a field transporter. They estimated the annual operating and maintenance cost of one harvest unit to be $580,000 (Thorsell et al.). The throughput capacity of a harvest unit is 341 tons per harvest day (Thorsell et al.). The number of harvest days per month by county depends upon soil moisture and the weather. Estimates of harvest days were based upon historical weather patterns (Reinschmiedt).

Field storage capacity was not limited. The cost of field storage that includes the cost of covering stored material with a plastic tarp was estimated at $2 per ton of biomass regardless of storage length. Field storage losses were estimated at 0.5% per month. Shipment and processing of biomass can be done in any of the 12 discrete periods (i.e., months of the year). In months when biomass is harvested, it may be placed in storage or transported directly from the harvest field to the biorefinery. Transportation distances between biomass-producing counties and biorefineries were determined by using online map miles from cities located near the center of the two counties. Transportation costs were estimated based upon an equation developed by Bhat, English, and Ojo.

Policy based upon the 2002 Farm Bill imposes two restrictions; frequency of harvest and harvestable days. The 2002 Farm Bill permits harvest of CRP land only once in three years. Theoretically, harvest could be conducted on a three-year rotation. However, since some of the acres are located in remote small fields with limited accessibility, for the base model it was assumed that no more than 25% of the CRP acres in a county could be harvested per year. The average CRP rental rate in the region was $35 per acre (U.S. Department of Agriculture, 2004). By policy, if the land were harvested for biorefinery feedstock, the rental rate would be reduced by 25% or an average of $9 per acre. For the modeling exercise, it was assumed that CRP owners would be paid $10 for each acre harvested to compensate for the reduction in CRP payment and removal of biomass. Since most of these acres are managed as native ranges, it was assumed that no commercial fertilizer, herbicides, or pesticides would be used.

The second policy restriction imposed by the 2002 Farm Bill limits the harvest window or the number of harvest days. The primary nesting and brood-rearing season during which harvest would not be permitted differs by state: April 15 to July 15, May 1 to July 1, and March 1 to July 1 for Kansas, Oklahoma, and Texas, respectively (U.S. Department of Agriculture, 2005). Permissible harvest seasons were defined by the state committees to be July 16 through August 15, July 2 through September 2, and July 2 through September 29 for Kansas, Oklahoma, and Texas, respectively (U.S. Department of Agriculture, 2005). Based on this regulation, harvesting of biomass was restricted to 30 days in Kansas, 60 days in Oklahoma, and 87 days in Texas. Thus, by policy, harvest of biomass from CRP grasslands in the case study region could begin on July 2 in Oklahoma and Texas, and on July 16 in Kansas. However, harvest cannot be conducted after August 15 in Kansas, September 2 in Oklahoma, and September 29 in Texas.

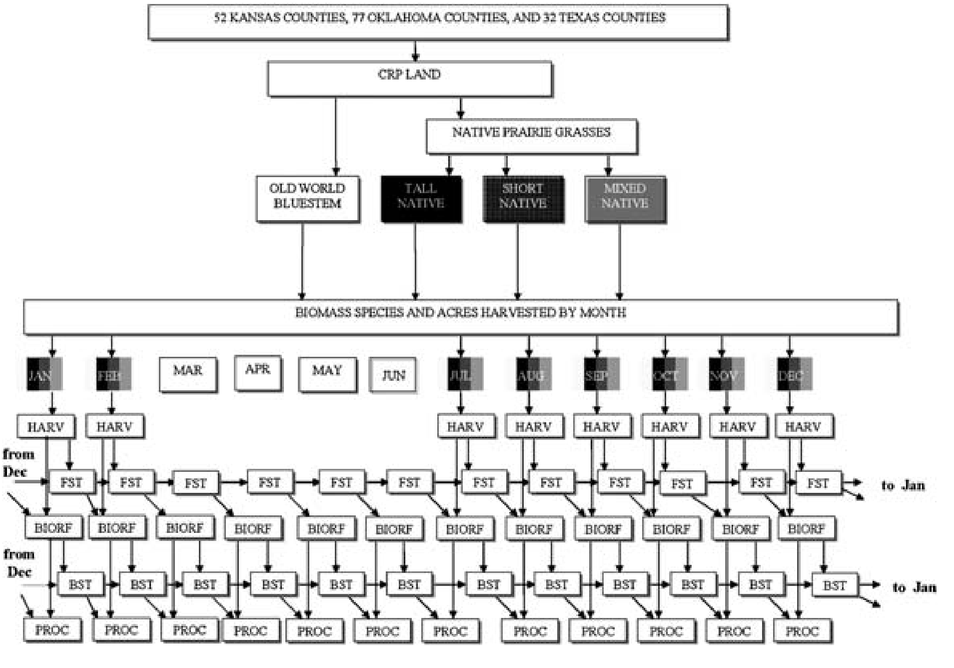
Three policy scenarios were modeled, Base-25, Flex-25, and Flex-50. The harvest day restrictions (30 days in Kansas, 60 days in Oklahoma, and 87 days in Texas) and the restriction to limit harvest to no more than 25% of the CRP acres in a county is referred to as Base-25. If the primary purpose of the harvest is to procure the carbon stored in the lignin and cellulose chains, harvest of native grasses in the region could begin in July and extend through February of the following year.

To determine the consequences of these two policy restrictions, two alternative policy scenarios were evaluated. For the first alternative, defined as Flex-25, the policy-imposed harvest day restriction is relaxed to permit an eight-month (flexible) harvest season. For the second alternative, defined as Flex-50, both the harvest day and harvest frequency restrictions are relaxed. For Flex-50, an eight-month (flexible) harvest season and 50% of the total CRP acres in a county are assumed available for harvest each year.

Model

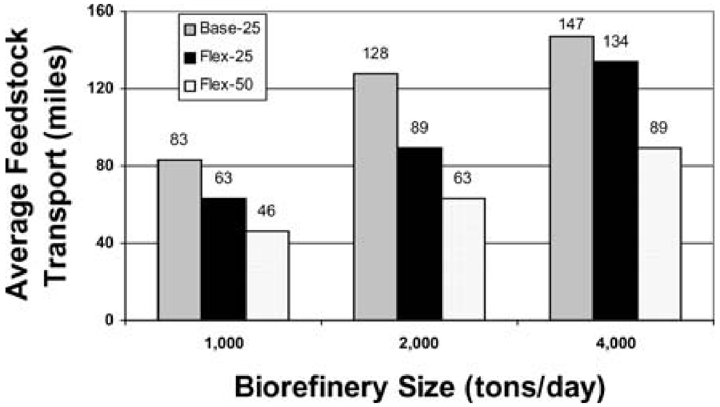
Each county in the study area (figure 1) is considered as a separate production region. The biorefinery locations were included in the model as binary variables and the model was solved to select the most economical location for each of three biorefinery sizes. The model was constrained to select only one biorefinery. Appendix tables A1, A2, and A3 describe the indices, parameters, and variables. Figure 2 includes a schematic chart of the levels of decisions modeled. The model simultaneously determines optimal decisions for all levels from harvest through

Figure 2. Schematic presentation of lignocellulosic biomass feedstock production, harvest, storage, transportation, and processing for an eight-month harvest season



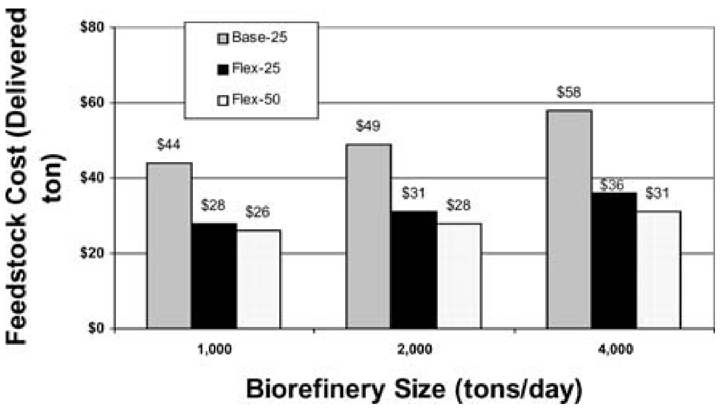
Note: HARV = Harvest; FST = Field Storage; BIORF = Biorefinery; BST = Biorefinery Storage; PROC = Processing.

Figure 3. Estimated average one-way distance to transport biomass to a biorefinery for three harvest situations and three biorefinery sizes



Note: Base-25 restricts harvest days to 2002 policy and total harvest to 25% of CRP acres per county per year. Flex-25 and Flex-50 enable a flexible (eight-month) harvest season but restrict total harvest to either 25% or 50%, respectively, of CRP acres per county per year.

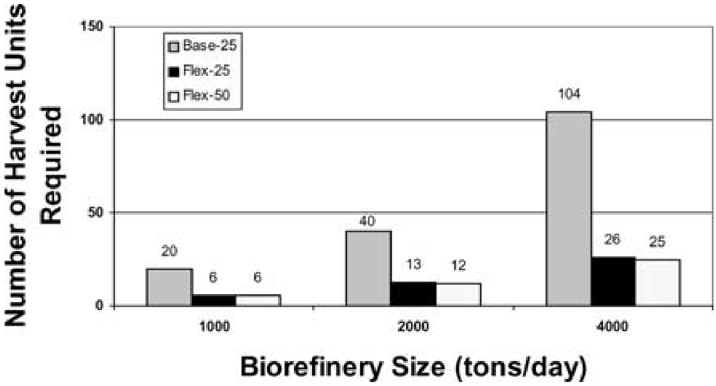
Figure 4. Estimated cost to deliver a ton of biomass to a biorefinery for three harvest situations and three biorefinery sizes



Note: Base-25 restricts harvest days to 2002 policy and total harvest to 25% of CRP acres per county per year. Flex-25 and Flex-50 enable a flexible (eight-month) harvest season but restrict total harvest to either 25% or 50%, respectively, of CRP acres per county per year.

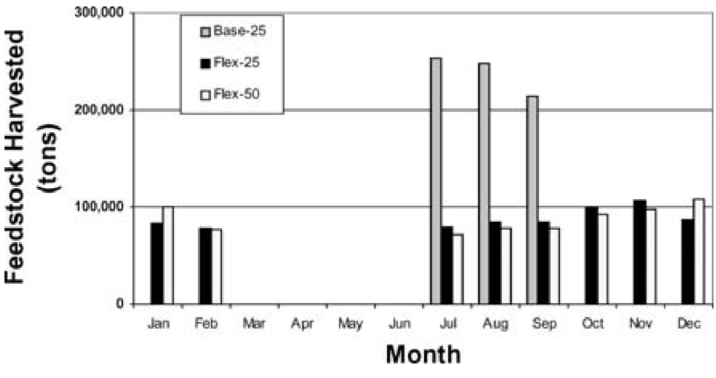
processing for all months, including harvest county, species, month, field storage, transport to biorefinery, biorefinery storage, and processing. The model is solved to determine the number of acres and tons of biomass harvested by county, species, month, number of harvest units, harvest cost, storage cost, transportation

Figure 5. Estimated number of harvest units with capacity to harvest a given quantity of biomass for three harvest situations and three biorefinery sizes



Note: Base-25 restricts harvest days to 2002 policy and total harvest to 25% of CRP acres per county per year. Flex-25 and Flex-50 enable a flexible (eight-month) harvest season but restrict total harvest to either 25% or 50%, respectively, of CRP acres per county per year.

Figure 6. Estimated quantity of feedstock harvested per month for a 2,000 tons per day biorefinery for three harvest situations and three biorefinery sizes



Note: Base-25 restricts harvest days to 2002 policy and total harvest to 25% of CRP acres per county per year. Flex-25 and Flex-50 enable a flexible (eight-month) harvest season but restrict total harvest to either 25% or 50%, respectively, of CRP acres per county per year.

cost, transportation distance, biorefinery location, and cost per ton of processed feedstock.

The model was solved for each of nine situations. The three policy scenarios, Base-25, Flex-25, and Flex-50 that reflect differences in harvestable days and frequency of harvest, were further differentiated by biorefinery feedstock requirements (either 1,000 or 2,000 or 4,000 tons of biomass per day) to determine the tradeoff between feedstock transportation cost and biorefinery size.

Results

Table 1 includes a summary of results from the nine scenarios. As the size of the biorefinery increases from 1,000 to 4,000 tons per day, the average one-way distance to transport biomass from the field to the biorefinery increases from 83 miles to 147 miles for the Base-25 system. This increases the transportation cost from $11.71 to $19.34 per ton. The increase in biorefinery size from 1,000 to 4,000 tons per day requires harvest of more acres, transportation from greater distances, and increases the cost to deliver a flow of feedstock from $44 to $58 per ton.

The results are similar for the Flex-25 scenario. Average transportation distance increases from 63 to 134 miles, and, transportation costs rise from $9.40 to $17.71 per ton as biorefinery size expands from 1,000 to 4,000 tons per day for the FIex-25 system. However, for the Flex-50 system that permits harvest of 50% of the CRP acres in a county (rather than 25%), the average transportation distance is reduced from 46 to 89 miles. By increasing the frequency of harvest, transportation costs could be reduced by $1.96 per ton for a 1,000 tons-per-day biorefinery and by $5.26 per ton for a 4,000 tons-per-day biorefinery. The average feedstock transport distances for each of the nine scenarios are graphed in figure 3. When the harvest frequency is increased (Flex-25 versus Flex-50), biomass feedstock is drawn from shorter distances, thereby substantially reducing transportation cost per ton. Both policy restrictions increase transportation distances and cost. Relaxing the harvest day restriction (Flex-25 versus Base-25) decreases average distance by 13-20 miles and cost by $1.63 to $2.31 per ton.

As described in table 1 and shown in figure 4, the policy restriction on harvest days as modeled with Base-25 relative to Flex-25, increases the cost to deliver a ton of biomass by $16 to $22 per ton depending upon biorefinery capacity. Furthermore, restricting harvest days and harvest frequency (Base-25 relative to Flex-50) increases the cost to deliver biomass by $18 to $27 per ton depending on biorefinery size. Restrictions on harvest days and frequency increase the harvest, storage and transportation costs. When both restrictions are relaxed (i.e., restrictions on harvest days and frequency, Flex-50 versus Base-25), the cost to deliver a ton of biomass feedstock declines from $44 to $26, from $49 to $28, and from $58 to $31 per ton for the 1,000, 2,000, and 4,000 dry tons per day biorefinery, respectively.

These findings are reasonably consistent with those reported elsewhere. For example, Cundiff and Harris reported a delivery cost of $54 per ton for switchgrass. Worley and Cundiff reported delivery cost of crop residues of $52 per ton. Gallagher et al. reported a delivery cost of $22 for crop residues; however, they did not include feedstock acquisition cost and storage cost. English et al. reported a delivery cost of $17 per ton for crop residues. But they did not include the cost of storing and transporting the crop residues to a biorefinery. Epplin reported a cost of $34 per ton for delivering switchgrass to a biorefinery.

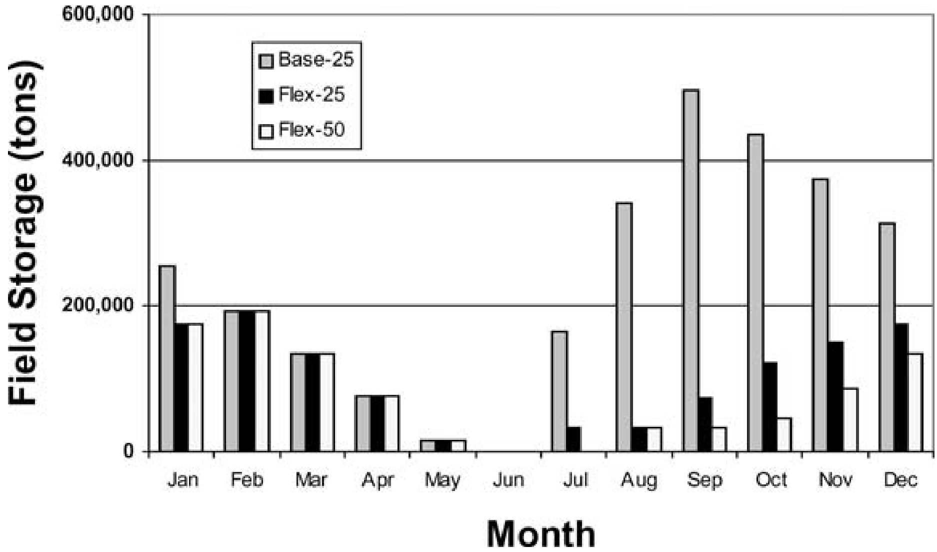
A coordinated set of harvest machines was defined as a harvest unit and included in the model as an integer investment activity. As the size of the biorefinery increases from 1,000 to 4,000 tons per day, the required number of harvest units increases from 20 to 104, for the Base-25 scenario, from 6 to 26 harvest units for the Flex-25 scenario, and from 6 to 25 harvest units for the Base-50 scenario (table 1

Table 1. Results of models solved to determine the cost to deliver a steady flow of biomass from Conservation Reserve Program acres

	Base-25			Flex-25			Flex-50		
	Biorefinery Size (tons/day)								
	1,000	2,000	4,000	1,000	2,000	4,000	1,000	2,000	4,000
Land rent cost ($/ton)	7.90	7.68	6.99	7.76	7.53	7.38	7.83	7.75	7.60
Harvest cost ($/ton)	23.15	23.14	30.10	9.87	10.69	10.69	9.87	9.87	10.28
Field storage cost ($/ton)	1.39	1.39	1.39	0.56	0.56	0.56	0.56	0.56	0.56
Transportation cost ($/ton)	11.71	17.04	19.34	9.40	12.41	17.71	7.44	9.39	12.45
Total cost of delivered feedstock ($/ton)	44.16	49.26	57.83	27.58	31.19	36.34	25.70	27.57	30.89
Harvested acres	282,209	548,755	998,906	273,467	531,011	1,040,307	276,109	546,934	1,072,492
Harvest units (number)[a]	20	40	104	6	13	26	6	12	25
Average investment in harvest machines ($'000)	11,800	23,600	61,360	3,540	7,670	15,340	3,540	7,080	14,750
Harvest months (number)[b]	3	3	3	8	8	8	8	8	8
Total biomass harvested (tons)[c]	357,051	714,425	1,428,074	352,507	705,431	1,410,380	352,366	705,013	1,410,452
Plant location (county)	Texas	Texas	Texas	Texas	Texas	Texas	Texas	Texas	Texas
Average distance hauled (miles)	83	128	147	63	89	134	46	63	89

[a] A harvest unit includes ten laborers, three mowers, three rakes, three balers, nine tractors, and one transport stacker.
[b] In Kansas, Oklahoma, and Texas, harvest days are restricted by policy. In the absence of policy restrictions, for the region of the study, biomass could be harvested on CRP grasslands from July through February.
[c] The biorefinery is expected to operate 350 days per year. The model accounts for storage losses. Total storage losses are greater when harvest is restricted.
The model considers CRP acres in selected counties of Kansas, Oklahoma, and Texas and 1,000, 2,000, and 4,000 tons per day biorefineries. Base-25 restricts harvest days to 2002 policy (30 days in Kansas, 60 days in Oklahoma, and 87 days in Texas) and harvest to 25% of CRP acres per county per year. Flex-25 enables a flexible (eight-month) harvest season but restricts harvest to 25% of CRP acres per county per year. Flex-50 enables a flexible harvest season but restricts harvest to 50% of CRP acres per county per year.

Figure 7. Estimated quantity of feedstock stored per month in the field for a 2,000 tons per day biorefinery for three harvest situations



Note: Base-25 restricts harvest days to 2002 policy and total harvest to 25% of CRP acres per county per year. Flex-25 and Flex-50 enable a flexible (eight-month) harvest season but restrict total harvest to either 25% or 50%, respectively, of CRP acres per county per year.

and figure 5). A 4,000 tons-per-day biorefinery under a Base-25 set of policies would require 936 tractors; 312 mowers, rakes, and balers; and 104 transport stackers. The estimated average investment in these harvest machines is approximately $61 million. If the policy-imposed harvest day limits and harvest frequency restrictions were relaxed to the level modeled with Flex-50, the number of harvest units required to harvest biomass for a 4,000 tons-per-day biorefinery could be reduced from 104 to 25 (figure 5). And, the average investment in harvest machines could be reduced from $61 million to $15 million.

Figure 6 includes a chart of the estimated quantity of feedstock harvested per month for a 2,000 tons-per-day biorefinery for each of the three policy scenarios. Monthly harvest is restricted by both the number of expected harvest days and by the endogenously determined number of harvest units. As indicated in table 1, the harvest day and harvest frequency policy restrictions as modeled by Base-25 requires the harvest of more tons of biomass since annual storage losses are greater with a restricted harvest season.

Figure 7 includes a chart of the estimated quantity of feedstock stored per month at field sites for a 2,000 tons-per-day biorefinery for each of the three policy situations. If the harvest season is restricted (Base-25), replenishment of storage reserves begins with the first permissible harvest month of July. Harvest and increase of field storage inventory continues throughout August and September. At the end of September, when by 2002 Farm Bill policy (Base-25) the harvest must cease, the combined field and biorefinery storage inventory must be sufficient to provide feedstock until harvest may be resumed the following July. Feedstock is removed from field storage until the end of June when inventory of both field storage and storage at the biorefinery are reduced to zero.

If the harvest day restrictions were relaxed (Flex-25), field inventory storage could increase more gradually from July through February (figure 7). The maximum quantity of required field storage for the Flex-25 scenario is less than half of that required for the restricted Base-25 scenario. This results in higher in-field storage costs (table 1). Similarly with a flexible harvest season and more frequent harvesting as modeled with Flex-50, less feedstock is placed in storage.

Conclusions

The Farm Security and Rural Investment Act of 2002 enabled managed harvest of CRP grassland acres for biorefinery feedstock use. This study was conducted to determine the cost to procure, harvest, store, and transport a flow of lignocellulosic biomass feedstock produced on CRP grasslands to an optimally located biorefinery and to determine how policies that restrict harvest frequency and harvest days influence cost. Three biorefinery sizes (either 1,000 or 2,000 or 4,000 tons of biomass per day) were considered for three different policy scenarios. The Base-25 scenario restricts harvest days and frequency to approximate the policy restrictions as implemented under the 2002 Farm Bill. The Flex-25 scenario relaxes the harvest day restriction and the Flex-50 scenario relaxes both the harvest day and harvest frequency restrictions.

It was determined that the estimated cost to deliver a flow of feedstock to a biorefinery ranged from $26 to $58 per ton depending upon the size of the biorefinery, the number of harvest days, and the harvest frequency. Increasing biorefinery feedstock requirements from 1,000 to 4,000 tons per day increases required transportation distances and the expected delivery cost by $14 per ton for the Base-25 model, by $9 per ton for the Flex-25 model, and by $5 per ton for the Flex-50 scenario. The estimated average one-way feedstock transportation distance ranged from 46 to 147 miles.

Given the underlying assumptions of the model, for the case study region, restricting the harvest days and harvest frequency would impose a rather substantial cost. The harvest day restriction (Base-25 versus Flex-25) more than doubles the expected harvest cost and expected field storage costs and increases the cost to deliver a ton of biomass by $17–21 per ton. The harvest frequency restriction is less costly. Estimated cost reductions achieved by doubling the frequency of harvest (Flex-50 versus Flex-25) are $2–5 per ton.

For the biomass biorefinery industry to develop and be economically feasible, it would be prudent for policy makers to enable an expanded harvest period for biomass for biorefinery processing. The logical harvest season for native grasses for biorefinery use is outside the nesting and brood season for grassland birds. A managed harvesting season could be designed to be in accordance with a well-stipulated conservation plan and in line with long-term protection of existing grasslands. Such a policy would not only benefit the environment and natural habitat for wildlife, but would also be in the interest of the biorefinery industry for sustainable and continuous flow of biomass feedstock to the biorefinery.

There are several limitations of the analysis. First, potential feedstock was limited to production from CRP grasslands. This restriction was imposed to enable a comparison of policies specific to use of CRP land. However, if the model were enhanced to include additional feedstocks such as crop residue, estimates of delivery cost would change. Second, it is assumed that no commercial fertilizer would be required to maintain productivity on the CRP acres. Productivity of native rangeland can be maintained without fertilization. However, additional research will be required to determine if productivity of CRP acres can be maintained if biomass is removed every second or fourth year.

A third limitation is that a specific conversion process was not modeled. The model is designed to maximize net present worth of a biomass-to-biorefinery industry. As noted, several competing conversion technologies including pyrolysis, liquefaction, and gasification, that would enable use of lignocellulosic biomass for biorefinery feedstock are under development. As estimates of biorefinery investment, maintenance, and operating costs, and of economies of size for the alternative conversion technologies become available, the model could be enhanced and used to compare the economics of the alternative technologies.

A fourth limitation is that the estimates are based upon 2004 price levels. As relative prices of key inputs such as harvest machinery and transportation costs change, the model could be updated to obtain more precise estimates of the cost of policies that restrict harvest of CRP grasslands.

Appendix

Model Equations

The objective function of the multi-region, multi-period, mixed integer mathematical programming model is given in equation (A1). Model parameters, variables, and indices are defined in tables A1, A2, and A3, respectively.

(A1)

$$\underset{q,x,xt,xs,A}{\text{Max}} NPW = \left\{ \sum_{m=1}^{M} \left[\sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{g=1}^{G} \rho_g q_{jsgm} - \sum_{i=1}^{I}\sum_{k=1}^{K} \gamma_k xsp_{ikm} - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{k=1}^{K} \tau_{ij} xt_{ijskm} \right] - \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{ft=1}^{FT} TAFC_{s,ft}\beta_{js} - \omega HU \right\} \times PVAF.$$

Subject to the following constraints:

Equation (A2) requires that the harvested acres may not exceed the total available CRP acres.

$$\text{(A2)} \qquad \sum_{m=1}^{M} A_{ikm} - \sum_{l=1}^{L} BP_{ikl} LAND_{ikl} \le 0, \qquad \forall i, k$$

Equation (A3) ensures that biomass harvested is equal to the available biomass in the field less any field losses. The yield adjustment factor, *YAD*, is used to adjust yield based upon harvest month.

(A3) $$x_{ikm} - YAD_{km}(A_{ikm}BYLD_{ik}) = 0, \qquad \forall i, k, m$$

The following constraint (equation (A4)) states that no acres may be harvested during months in which the yield adjustment factor is equal to zero.

(A4) $$A_{ikm} = 0 \quad \text{if } YAD_{km} = 0, \qquad \forall i, k, m$$

Equation (A5) states that in each month and at each county, the sum of biomass shipped to the biorefinery and biomass put in storage should equal the sum of current production and usable portion of stored biomass.

(A5) $$\sum_{j=1}^{J}\sum_{s=1}^{S} xt_{ijskm} + xs_{ikm} - \theta_{ik}xs_{ikm-1} - x_{ikm} = 0 \qquad \forall i, k, m$$

Equation (A6) ensures that quantity of biomass shipped out plus that lost in in-field storage balance with total biomass harvested.

(A6) $$\sum_{m=1}^{M} x_{ikm} - \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{m=1}^{M} xt_{ijskm} - (1-\theta_{ik})\sum_{m=1}^{M} xs_{ikm} = 0, \quad \forall i, k$$

Equation (A7) states that, in each month, the quantity of biomass harvested plus that quantity removed from storage must equal the quantity of biomass transported from biomass-producing counties to the biorefinery plus the quantity placed in storage.

(A7) $$\sum_{i=1}^{I}\sum_{k=1}^{K}(x_{ikm} + xsn_{ikm}) - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{k=1}^{K} xt_{ijskm} - \sum_{i=1}^{I}\sum_{k=1}^{K} xsp_{ikm} = 0, \quad \forall m$$

Equation (A8) states that the sum of harvest units used in each month may not exceed the total number of harvest units endogenously determined by the model.

(A8) $$\sum_{i=1}^{I} xhu_{im} - HU \leq 0, \quad \forall m$$

Equation (A9) states that, in each biomass-producing county and month, the quantity of biomass harvested may not exceed the combined harvesting capacity of the number of harvest units determined by the model.

(A9) $$\sum_{k=1}^{K} x_{ikm} - xhu_{im}CAPHU_{im} \leq 0, \quad \forall i, m$$

The following capacity constraint (equation (A10)) links biomass processing capacity at the biorefinery to the binary variable. If $\beta_{js} = 1$, $CAPP_s\ \beta_{js} = CAPP_s$, the processing capacity upper bound, and the total processing at the biorefinery in that month will be bounded by $0 \leq q_{jsem} \leq CAPP_s$.

$$q_{jsem} - CAPP_s \beta_{js} \leq 0, \qquad \forall j, s, m \tag{A10}$$

Equation (A11) links biomass storage capacity at the biorefinery to the binary variable. The total biomass storage at the biorefinery will be bounded by $0 \leq xs_{jkm}$ $\leq CAPS_s$. If $\beta_{js} = 0$, $CAPS_s\ \beta_{js}$ will be equal to zero and since xs_{jkm} cannot assume negative values, it will also be zero.

$$\sum_{k=1}^{K} xs_{jkm} - CAPS_s \beta_{js} \leq 0, \qquad \forall j, s, m \tag{A11}$$

Equation (A12) imposes the constraint that total biomass processed or stored at the biorefinery may not exceed the total biomass supply.

$$\sum_{i=1}^{I} xt_{ijskm} + \phi_{jk} xs_{jkm-1} - xs_{jkm} - xp_{jskm} = 0, \qquad \forall j, k, m, s \tag{A12}$$

Equation (A13) balances total biomass delivered to the biorefinery with the sum of processed biomass and on-site storage losses.

$$\sum_{i=1}^{I} \sum_{m=1}^{M} xt_{ijskm} - (1 - \phi_{jk}) \sum_{m=1}^{M} xs_{jskm} - \sum_{m=1}^{M} xp_{jskm} = 0, \quad \forall j, k, s \tag{A13}$$

Equation (A14) is a constraint that imposes minimum biomass inventory at the biorefinery.

$$\sum_{k=1}^{K} xs_{jkm} - MBINV_s \beta_{js} \geq 0, \qquad \forall j, m, s \tag{A14}$$

Equation (A15) allows the model to assume a Leontief production function at the biorefinery.

$$q_{jsgm} - \sum_{k=1}^{K} \lambda_{kg} xp_{jskm} \leq 0, \qquad \forall g, j, m, s \tag{A15}$$

The constraint below (equation (A16)) represents an upper bound on the total number of biorefineries, assumed here to be equal to one.

$$\sum_{j=1}^{J} \sum_{s=1}^{S} \beta_{js} \leq 1 \tag{A16}$$

Table A1. Model indices and descriptions

Index	Description and Member Elements
Main Sets	
m	Month: m = {Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec, Jan, Feb}
j	Set of prospective biorefinery locations: j = {11 sites}
s	Set of biorefinery sizes: s = {Small, Medium, Large}
g	Vector of pseudo-product and by-products
i	Set of biomass supply counties: i = {Each of biomass supply counties in the study}
k	Set of feedstock species: k = {Old world bluestem, Native mixed prairies}
ft	Set of facilities. In this case, ft = {Processing facility, Storage facility}
l	Land Category: l = {CRP}

Table A2. Description of model parameters

Parameter	Description
ρ_g	Price per unit of pseudo-output g
γ_k	Cost of storing a ton of biomass k in the field
τ_{ij}	Round-trip cost of transporting a ton of biomass from county i to biorefinery location j
ω	Annualized cost of owning and operating a harvest unit
θ_{ik}	Proportion of biomass k stored in county i that is usable a month later
ϕ_{jk}	Proportion of biomass k stored at biorefinery j that is usable a month later
λ_{kg}	Quantity of pseudo-output g produced from a ton of biomass k
$LAND_{ik}$	Total acres of land producing biomass k in county i
BP_{ikl}	Proportion of land of category l in county i with biomass k available for harvesting for biorefinery use
YAD_{km}	Yield adjustment factor for biomass k if harvested in month m
$BYLD_{ik}$	Maximum yield (tons/acre/year) of biomass k at county i
$TAFC_{sft}$	Amortized fixed cost of constructing and operating facility ft of biorefinery size s
$CAPHU_{im}$	Capacity of a harvest unit in county i month m
$CAPP_s$	Processing facility capacity associated with biorefinery size s
$CAPS_k$	Biomass storage facility capacity associated with biorefinery size s (tons of biomass)
$MBINV_s$	Minimum biomass inventory for biorefinery size s (tons/month)
$PVAF$	Present value of annuity factor, where the annuity factor is the annual net benefit for the industry
r	Market discount rate, used in the computation of $PVAF$
t	Biorefinery useful life used in the computation of $PVAF$

Table A3. Description of variables

Variable	Description
NPW	Overall net present worth of the biorefinery system
q_{jsgm}	Quantity of output *g* produced in month *m* by a biorefinery of size *s* at location *j*
A_{ikm}	Acres harvested at county *i* in month *m* of biomass *k*
xsp_{ikm}	Tons of biomass *k* harvested in month *m* and stored in county *i*
xt_{ijskm}	Tons of biomass *k* transported in month *m* from county *i* to a biorefinery of size *s* at location *j*
x_{ikm}	Tons of biomass *k* harvested in month *m* at county *i*
xs_{ikm}	Tons of biomass *k* stored at county *i* in month *m*
xsn_{ikm}	Tons of biomass *k* removed from storage at county *i* in month *m*
xhu_{im}	Proportion of a harvest unit used in county *i* in month *m*
HU	Total number of harvest units used
xs_{jkm}	Tons of biomass *k* stored at biorefinery location *j* in month *m*
xp_{jskm}	Tons of biomass *k* processed by a biorefinery of size *s* at biorefinery location *j* in month *m*
β_{js}	A binary variable associated with biorefinery size *s* at location *j*

The following constraints (equation (A17)) are the nonnegativity conditions.

(A17) $$A_{ikfm},\ x_{ikm},\ xs_{ikm},\ xs_{jkm},\ xt_{ijskm},\ xp_{jskm},\ q_{jsgm} \geq 0$$

Equation (A18) restricts values of the binary variable to the set of zero and one.

(A18) $$\beta_{js} \in \{0, 1\}$$

Finally, the last constraint (equation (A19)) restricts the number of the harvest units to nonnegative integer values.

(A19) *HU* is an integer variable.

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